Space Goals and Resource Prospecting - 2

"ENABLING SUSTAINABLE TRANS EARTH HABITATION"

SRR/PTMSS Workshop, June 2018
Tech Session 1

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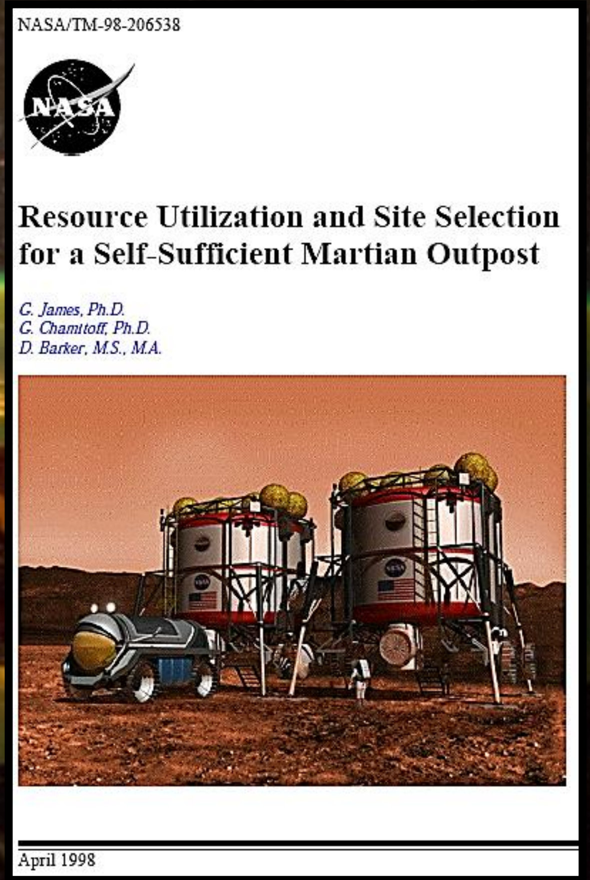
MAXD, Inc.


NASA/TM-98-206538

Resource Utilization and Site Selection for a Self-Sufficient Martian Outpost

G. James, Ph.D.
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D. Barker, M.S., M.A.

April 1998

Today’s Scope:

1) …2 years ago…
2) Spaceflight “Destination” Cycle and News
3) How and Why for Prospecting in Space
    a. System Engineering and Technology Readiness Levels – it all takes time…
        - Example – Mars
    b. Remote Sensing & Ground Truth
    c. Planetary Resource Management Guide Development
        - Example - the Moon
4) Changing Goals, Mindsets, Vocabulary and Requirements from “Exploration” and “Science” to “Settlement” (i.e. Permanent Habitation)
5) A spaghetti Bowl of Variables and Actors…Much More to Consider to Attain Viability for Mining in Space

Take Away SRR/PTMSS Workshop 2016

1) No “resource” is as important and versatile (i.e. a design driver) as Water.
2) No “resource” other than water on Mars has been identified to a significant level for mining/reclamation confidence.
3) Instrument resolution needs to be significantly enhanced.
4) Stakeholder community needs to focus its goals, message and build synergy; i.e. no more human vs. robotic, science vs. ISRU, etc.
5) Stakeholder community needs to determine how to find long-term, sustainable and secure levels of funding independent of government changes.
6) At the largest scales, time may not be on our side for many reasons (no rose colored glasses here).
7) At the prospecting, mission and hardware design and testing levels, we could lose many of the next best Mars launch opportunities (>> Sep-2022, Oct-2024, Nov-2026, Dec-2028, Feb-2031, May-2033, Jul-2035 & Sep-2037) if objectives and goals are not aligned across all stakeholder communities.

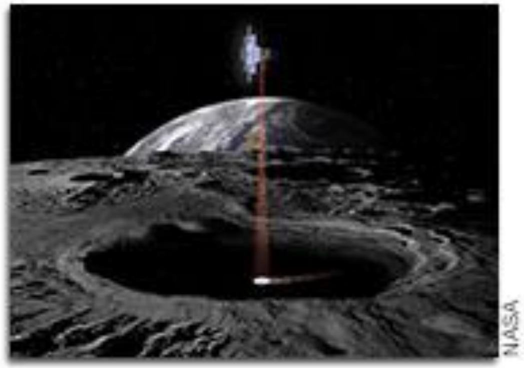
ONCE AGAIN, the pendulum has swung across the gamut of destinations…

The Past Two Years and In the News

- $20 million Google Lunar XPRIZE not claimed after 10 years – not as easy as everyone had hopped!

Resource Prospector was canceled. What kind of message does this send regarding goals and commitment?

The "Journey To Mars“ is no longer the agency's prime goal for human spaceflight.



And just a week ago, *NASA announced it had selected 10 companies to conduct studies in* In-Situ Resource Utilization:

- *Blue Origin, Kent, Washington*
- *United Launch Alliance*
- *University of Illinois*
- *UTC Aerospace Systems*
- *BlazeTech Corporation*
- *Paragon Space Development Corporation*
- *Skyhaven Systems*
- *Teledyne Energy Systems*
- *Honeybee Robotics Spacecraft Mechanisms Corporation*
- *OxEon Energy LLC*

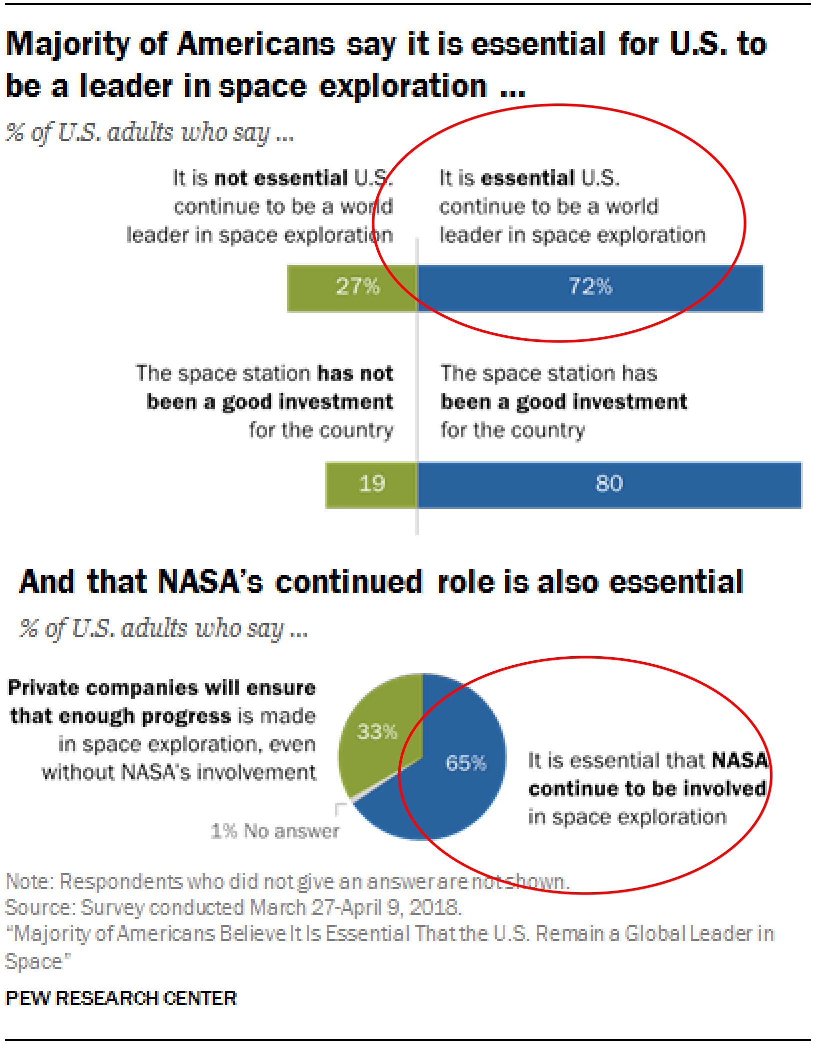
https://www.nasa.gov/isru

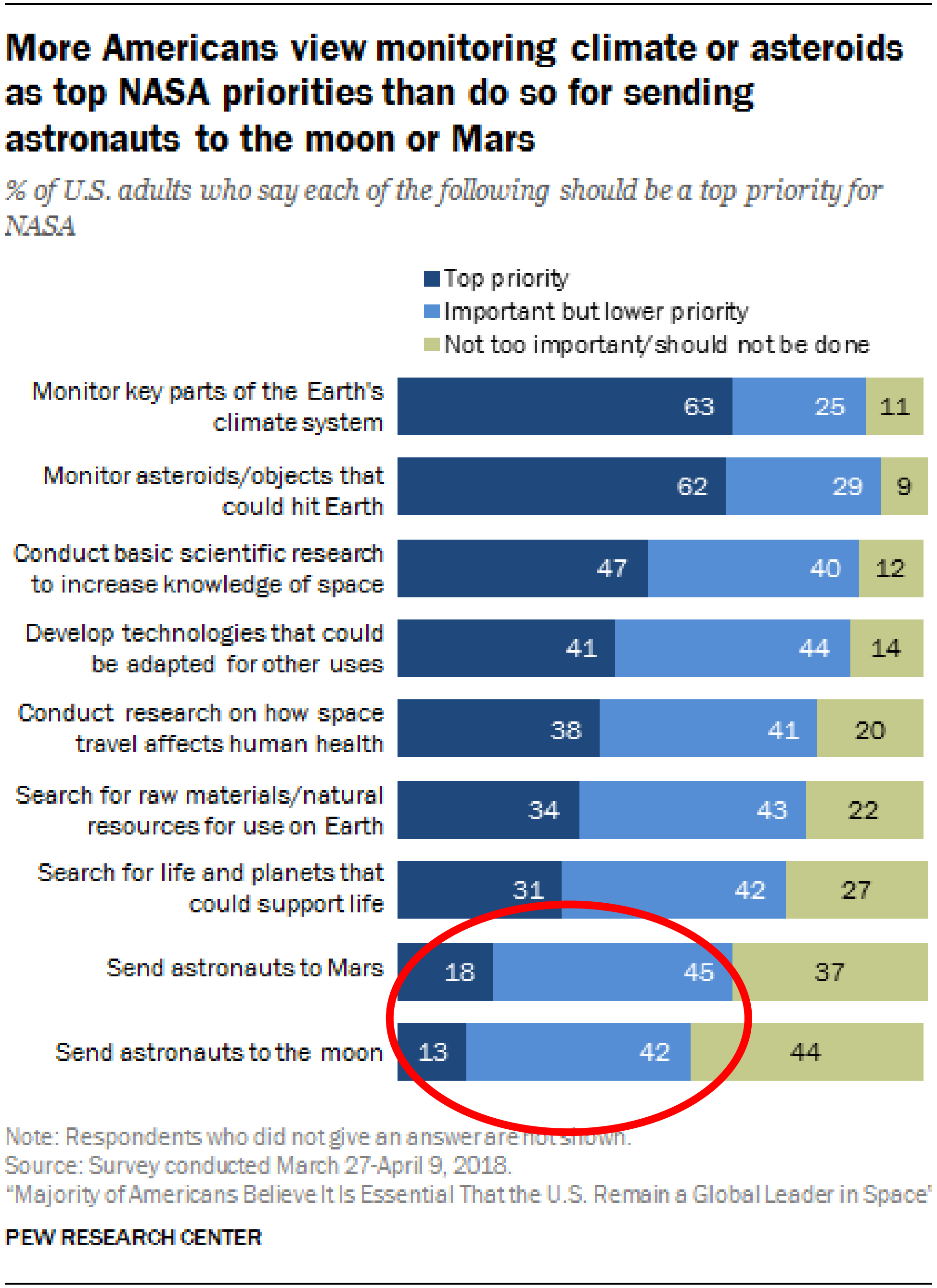
Like much regarding space, there is an active “social media underground” of interest and hopeful wishing.

Public Support in the News

- "Essential for U.S. to be a leader in space….72%"
- "Only 13% say the same of putting astronauts on the moon."

How can any organization garner support in this environment for mining resources in space given a lack of pragmatic and sustainable paths forward, significant lack of knowledge as to amounts and locations, and no actual end users in place?

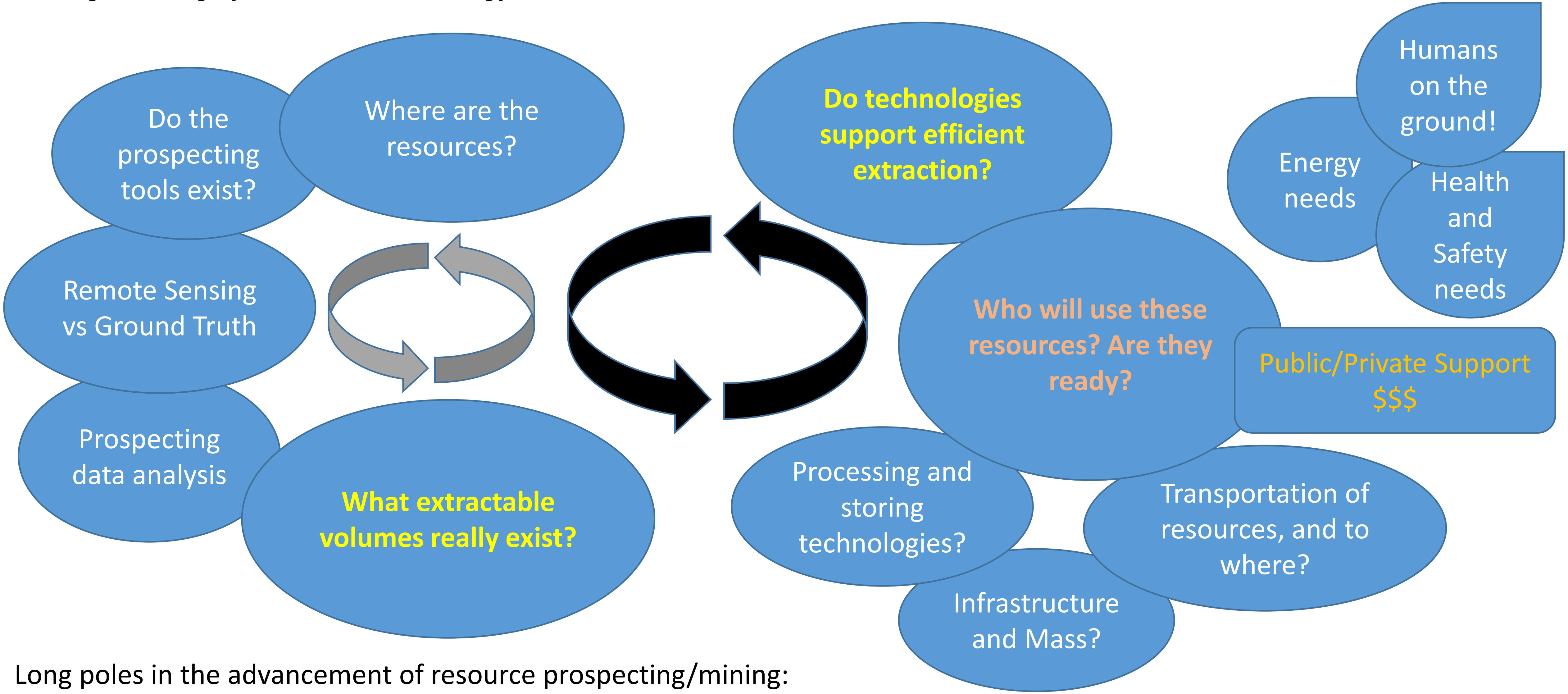




http://www.pewinternet.org/2018/06/06/majority-of-americans-believe-it-is-essential-that-the-u-s-remain-a-global-leader-in-space

Prospecting and Mining and Users

The economics of mining in space is a *chicken-egg problem*. One made even more complex and difficult when prospecting time is added with the standard space hardware development process (based on Systems Engineering cycles and Technology Readiness Levels).



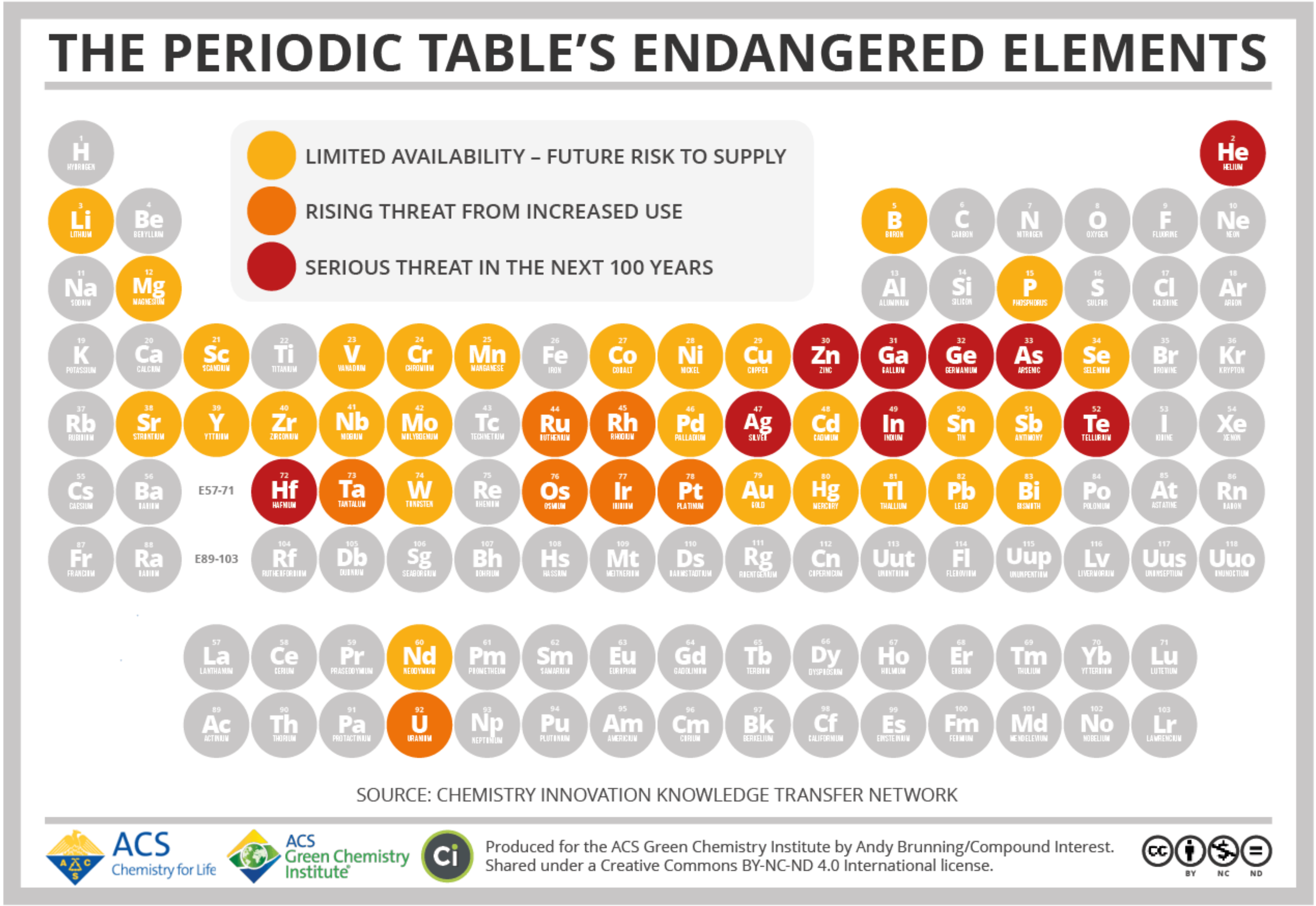
Long poles in the advancement of resource prospecting/mining:
The primary one is $$$ (as usual), but even with all the $$$, only so much can be accomplished in a given amount of time.

Will Resources Ever Be Returned to Earth?

There are 44 highly used elements that will face increasing supply limitations and incur cost increases for dependent products and heighten geopolitical friction in the coming years.

Can space mining bridge this gap?

Can a business model be made to find, extract, store, process, transport and return space resources to the surface of the Earth?

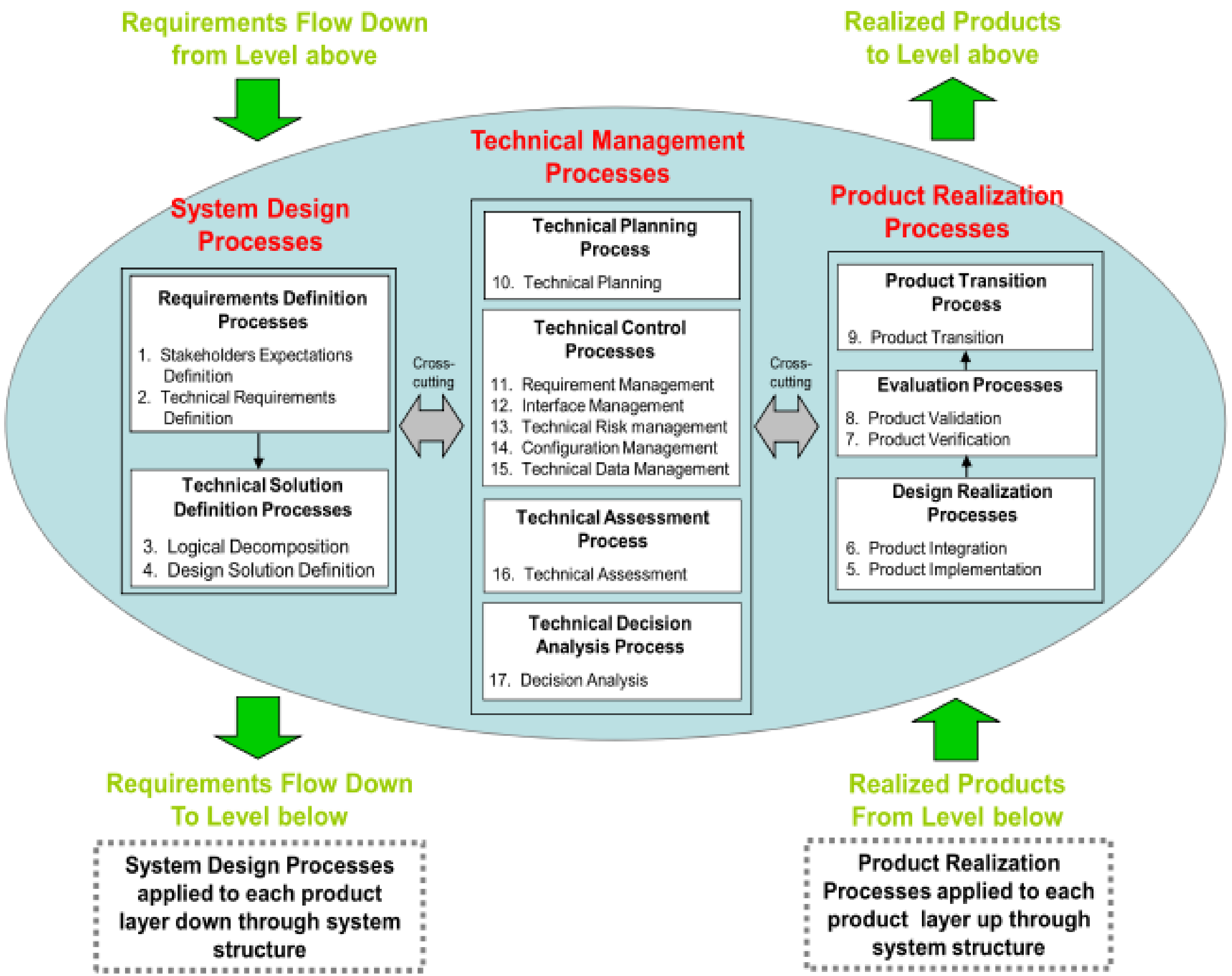


https://www.acs.org/content/acs/en/greenchemistry/research-innovation/research-topics/endangered-elements.html

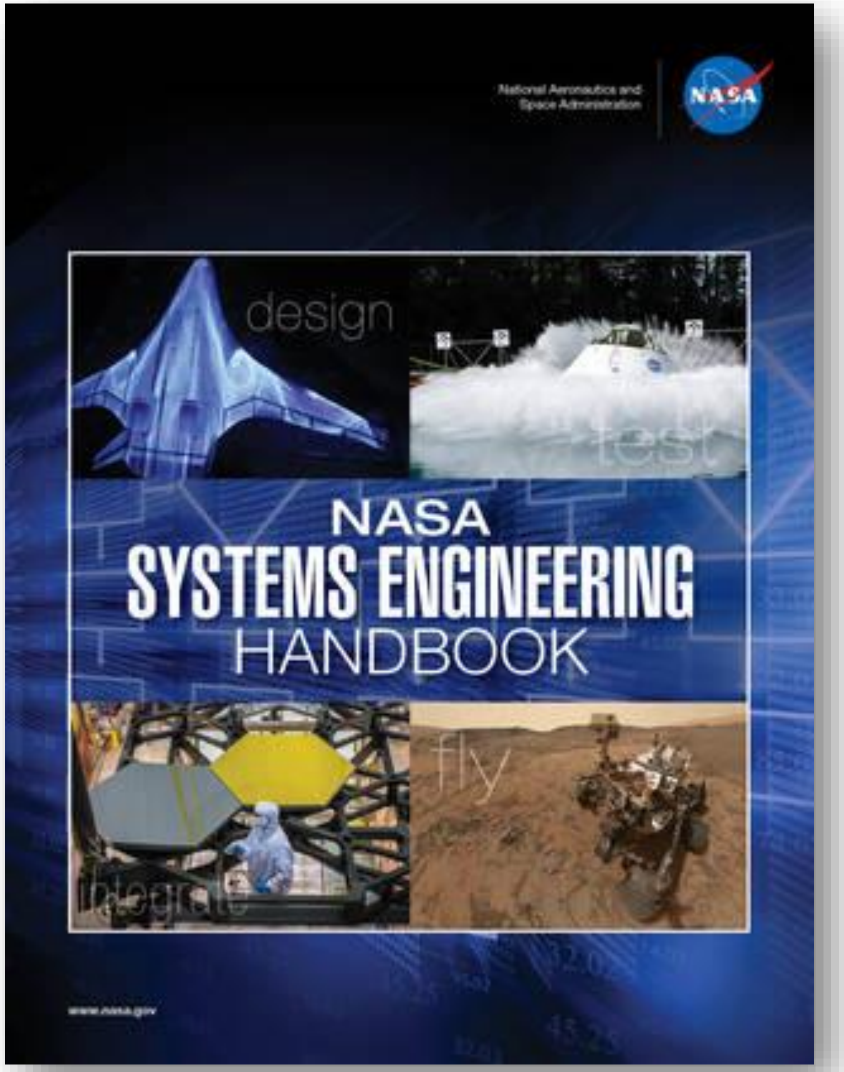
https://www.weforum.org/agenda/2017/11/the-periodic-table-of-endangered-elements/

+ Graedel et al., 2015 - Criticality of metals and metalloids

Systems Engineering Cycles



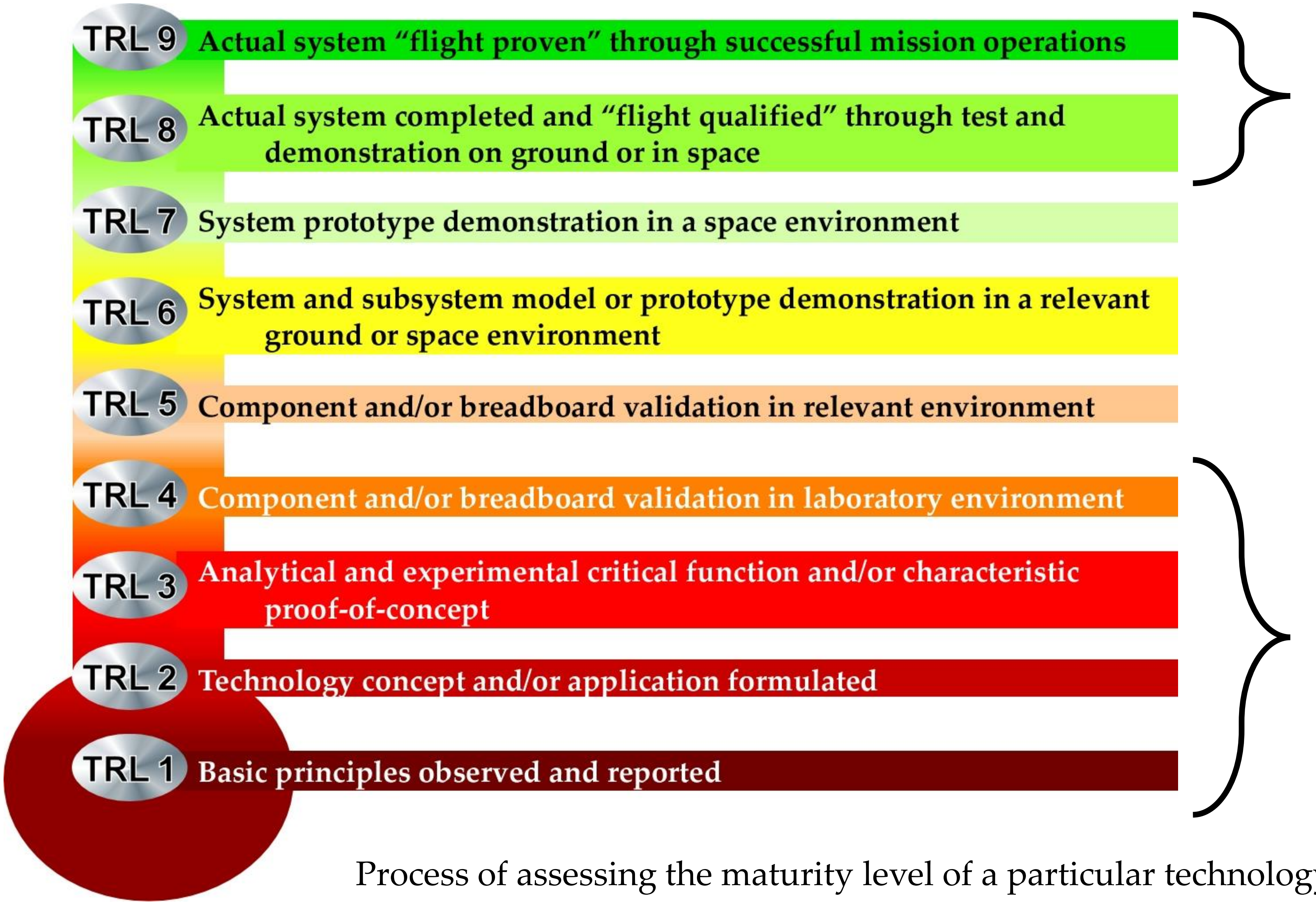
NASA SP-2016-6105 Rev2



https://www.nasa.gov/connect/ebooks/nasa-systems-engineering-handbook

Systems Engineering cycle is much like the scientific process is highly cyclic and time consuming.

Technology Readiness Levels



High level prospecting – remote sensing – commercially semi-quantitative – accesses the very top surface of objects

For extraterrestrial mining, extraction, processing, storage and transport.

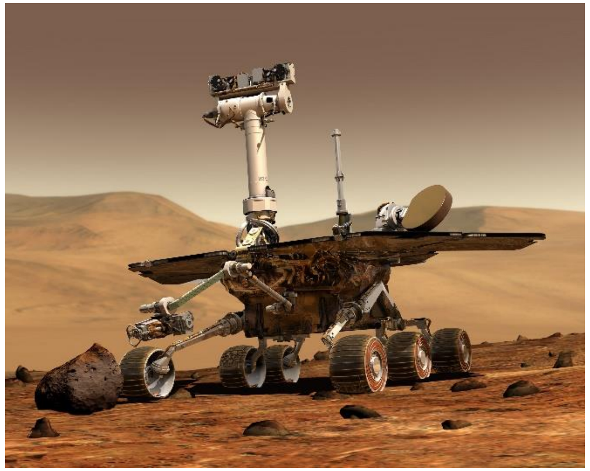
Process of assessing the maturity level of a particular technology for a given application.

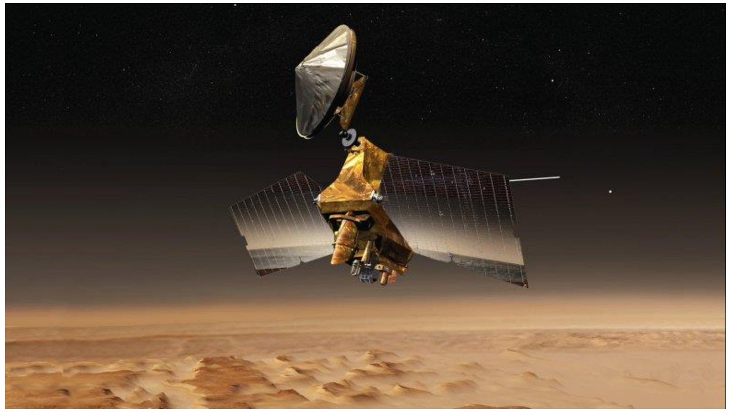
Mars Mission Development History

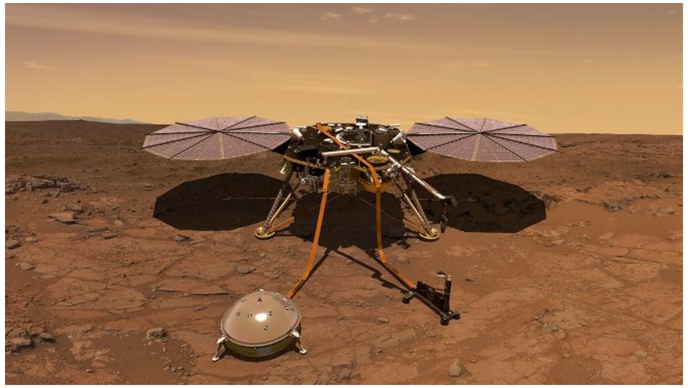
The total average cradle-to-launch is 4.6 years and has increased since 2005 on average to 5.8 years.

	Mariner 4	Mariner 9	Viking 1 (L/O)	Viking 2 (L/O)	Mars Observer	Mars Pathfinder	MGS	Mars Climate Orbiter	Mars Polar Lander	2001 Mars Odyssey	MER Spirit	MER Opportunity	MRO	Phoenix	MSL Curiosity	Maven	Insight
Selected or first $	1961	1967	1969	1969	1985	1994	1994	1995	1995	2000	2000	2000	2000	2005	2003	2008	2011
Launch	11/28/1964	5/30/1971	8/20/1975	9/9/1975	9/25/1992	12/4/1996	11/7/1996	12/11/1998	1/3/1999	4/7/2001	6/10/2003	7/7/2003	8/12/2005	8/4/2007	11/26/2011	11/18/2013	5/5/2018
Died	12/21/1967	10/27/1972	11/13/1982	4/11/1980	8/21/1993	9/27/1997	11/2/2006	9/23/1999	12/3/1999	6/12/2018	3/22/2010	6/12/2018	6/12/2018	11/2/2008	6/12/2018	6/12/2018	6/12/2018
Total Ops Days	1118	516	2642	1676	330	297	3647	286	334	6275	2477	5454	4687	456	2390	1667	38
Cradle-Launch (dys)	1427	1610	2422	2442	2824	1068	1041	1440	1463	462	1034	1061	1898	914	3100	1860	2561
Cradle-Launch (yrs)	3.9	4.4	6.6	6.7	7.7	2.9	2.9	3.9	4.0	1.3	2.8	2.9	5.2	2.5	8.5	5.1	7.0
Cost ($mil)	554	137	500	500	813	175	154	193.1	110	297	400	400	720	386	2500	671	829
2018 Cost ($mil)	4450	842	2314	2314	1443	278	244	295	164	418	541	541	918	4635	2767	717	829

* does not include mission extension costs



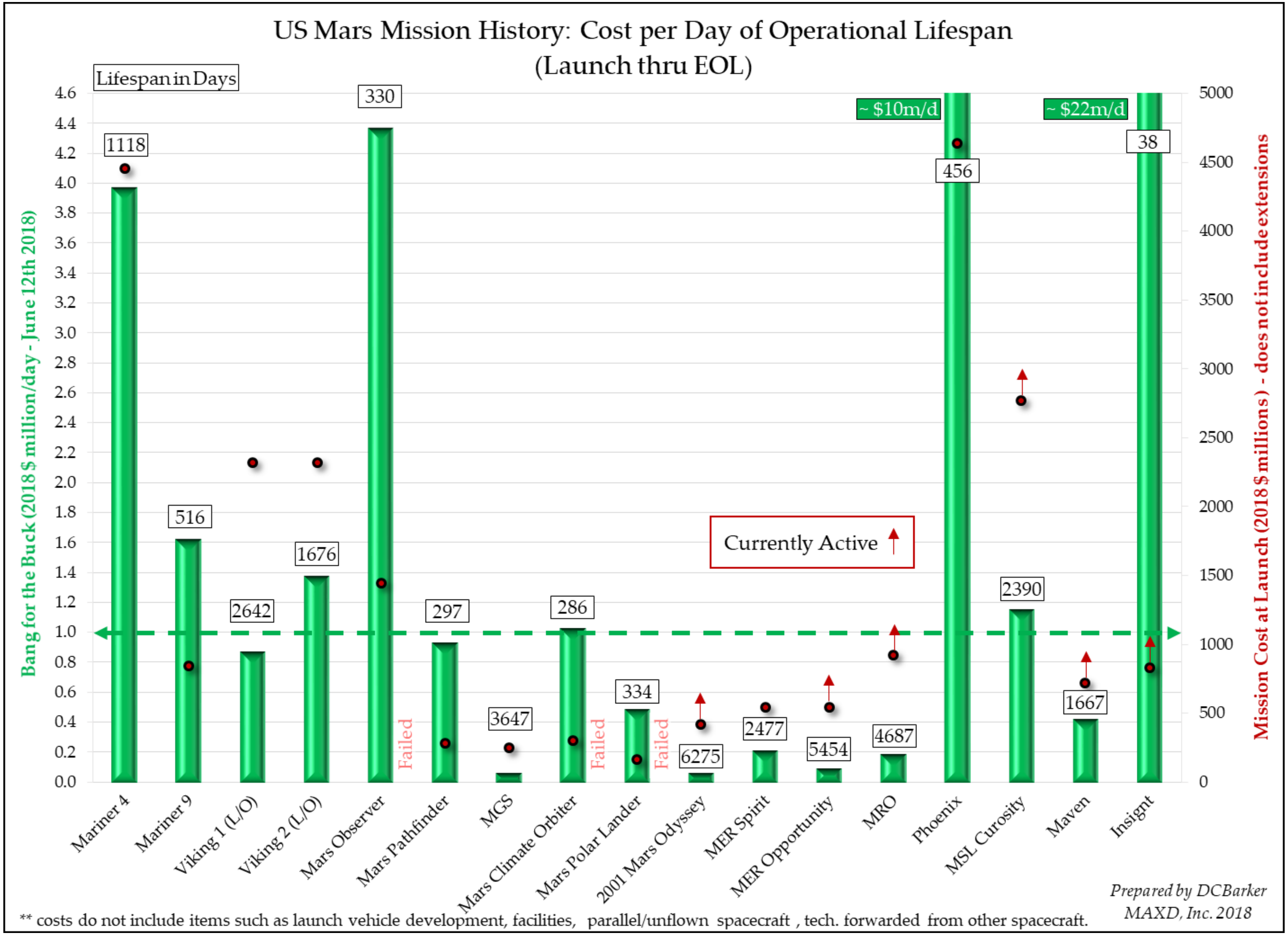




Source: NASA Budget Estimates Fiscal Years 1961-2017 (see backup slides)

History & Costs: Designing for Sustainability, Longevity and Adaptability

Go Forward Design Philosophy:
Require that all remote sensing satellites be designed for multi-mission support roles such as communications & Data relays, proxy GPS installations, ground systems monitoring, etc.



Some light Reading:

NASA BUDGET HISTORY

NASA Estimates of Appropriations Fiscal Year 1961, Vol. 1 & 2
Budget Estimates Fiscal Year 1962, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1963, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1964, Vol. 1, 2, 3, 4 & 5
Budget Estimates Fiscal Year 1965, Vol. 1, 2, 3, 4, 5, 6 & 7
Budget Estimates Fiscal Year 1966, Vol. 1, 2, 3, 4, 5, 6 & 7
Budget Estimates Fiscal Year 1967, Vol. 1, 2, 3, 4, 5, 6 & 7
Budget Estimates Fiscal Year 1968, Vol. 1, 2, 3 & 4
Budget Estimates Fiscal Year 1969, Vol. 1, 2, 3 & 4
Budget Estimates Fiscal Year 1970, Vol. 1, 2, 3 & 4
Budget Estimates Fiscal Year 1971, Vol. 1, 2, 3 & 4
Budget Estimates Fiscal Year 1972 Vol. 1, 2, 3 & 4
Budget Estimates Fiscal Year 1973, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1974, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1975, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1976, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1977, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1978, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1978, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1979, Vol. 1, 2 & 3 + Supplement
Budget Estimates Fiscal Year 1980, Vol. 1, 2 & 3 + Supplement
Budget Estimates Fiscal Year 1981, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1982, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1983, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1984, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1985, Vol. 1, 2 & 3
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Budget Estimates Fiscal Year 1987, Vol. 1, 2 & 3
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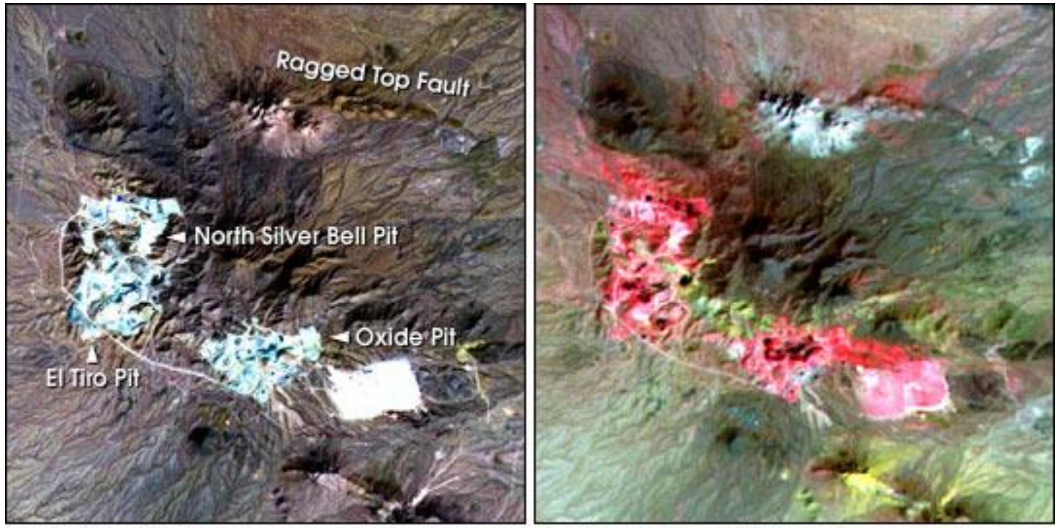
Budget Estimates Fiscal Year 1992, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1993, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1994, Vol. 1, 2 & 3
Budget Estimates Fiscal Year 1995, Vol. 1 & 2
Budget Estimates Fiscal Year 1996, Vol. 1 & 2
Budget Estimates Fiscal Year 1997, Vol. 1 & 2
Budget Estimates Fiscal Year 1998, Agency Summary
Budget Estimates Fiscal Year 1999, Agency Summary
Budget Estimates Fiscal Year 2000, Agency Summary
Fiscal Year 2000 Budget Estimates
Fiscal Year 2001 Budget Estimates
Fiscal Year 2002 Budget Estimates
Fiscal Year 2003 Budget Estimates
Fiscal Year 2004 Budget Estimates
President’s FY 2005 Budget Request
President’s FY 2006 Budget Request + Supplement
President’s FY 2007 Budget Request
FY 2008 Budget Estimates, President’s FY 2008 Budget Request
Fiscal Year 2009 Budget Estimates , President’s FY 2009 Budget Request
Fiscal Year 2010 Budget Estimates
President’s FY 2011 Budget Request Summary
Fiscal Year 2012 Budget Estimates*
Fiscal Year 2013 Budget Estimates* – PP summary
FY 2014 Budget Estimates* – PP summary
Fiscal Year 2015 Budget Estimates* – PP summary
Fiscal Year 2013 Budget Estimates – PP summary
Fiscal Year 2017 Budget Estimates – PP summary
FY 2019 Budget Estimates – PP summary

Prospecting from Space

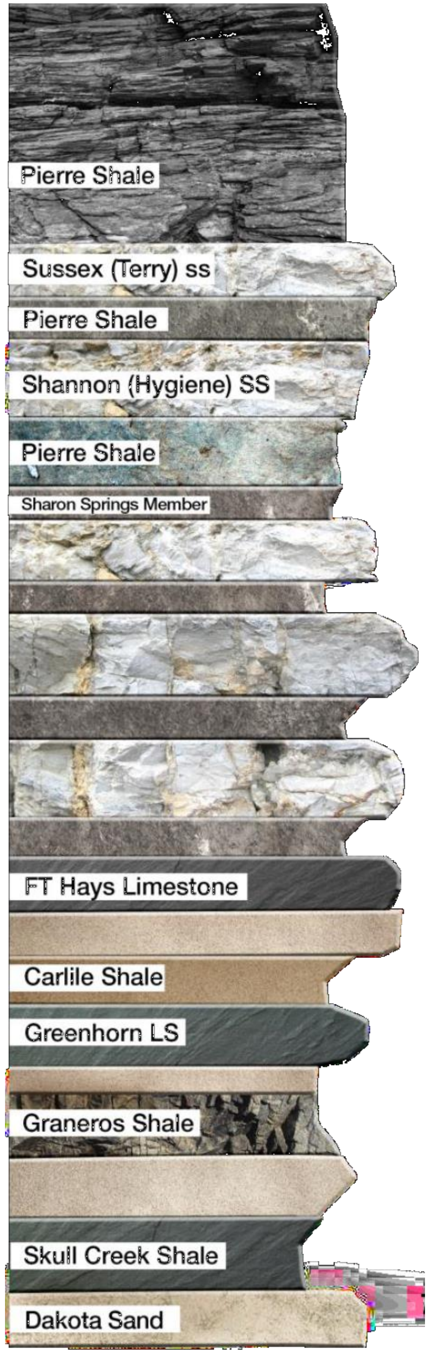
- The history of using remote sensing for the purpose of prospecting by providing an in-depth ability to find and detect relevant geological information only goes back 20 years with the launch of the **ASTER** satellite.
- As with all remote sensing, prospecting knowledge is highly limited due to many variables including: spatial resolution, deposit morphology, ground cover, instrument wavelength, physical interactions, relevant material spectral databases in a given environment, etc.
- Usually only get information from the very tops of surfaces (ground penetrating radar (GPR) and gamma ray spectroscopy (GRS) being exceptions).
- Therefore, in order to determine the highest probability of establishing a “commercially recoverable” resource, **ground truth is required** to prove the viability of establishing mining operations.

Copper Prospecting



near infrared false color

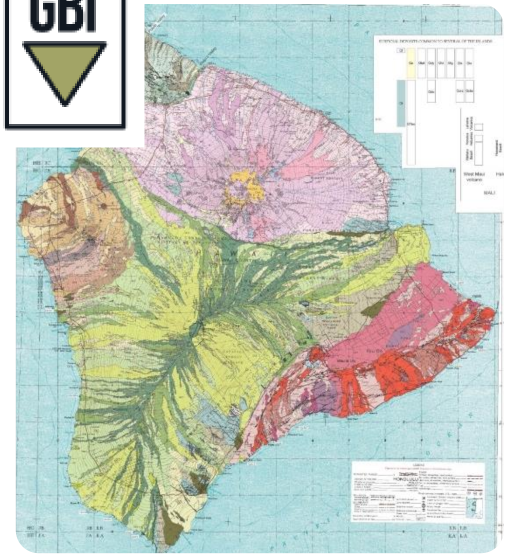
shortwave infrared false color



> 7000 feet

https://earthobservatory.nasa.gov/Features/ASTERProspecting

Ground Truth (Prospecting, Mining & Construction)



BASALT ROCK LIBERATION TECHNIQUES

- Drill/Blasting
- Clawing/Ripping
- Freezing/Heating
- Hydraulic Splitters
- Hydraulic Hammers
- Kinetic Drop Hammers

ON EARTH
TRL 1
&
MASS TO
ORBIT

BASALT LAVA
DEPOSIT/FLOW
VARIABILITY

Unconfined Compressive Strengths of < 1,000 psi to >30,000 psi

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Prospecting in Space

Landing a human expeditions to conduct prospecting operations and confirm robotic remote sensing data is ***analogous*** to drilling an exploration well in the petroleum industry. The most costly and risky of the prospecting steps.

Onshore exploration wells cost upwards of $10 million depending on depth and with advanced (equivalent **TRL10**) technologies. Offshore wells can go above $100 million. Current Permian Basin and Eagle Ford production drilling costs range between about $5 and $10 million. And each of these are *expecting to make money* on these activities.

In space, launch costs alone outweigh these drilling costs; Falcon 9 at $62 million and Falcon Heavy ~$90 million. This does not include costs for preliminary robotic prospecting costs or development of human systems, surface infrastructure, tools, ground support, etc.

Developing/Defining a **Planetary Resource Management System (PRMS)**

Purpose: to develop objective, data driven guidelines for focusing the development of resources, mission goals, hardware and designs for prospecting missions towards enabling space-resource acquisition and concurrent human settlement site selection.

The concept of a Petroleum Resources Management or Classification System began in the 1970's to address actual or perceived limits in highly used resources. Ongoing evolution of this resource rating and classification scheme accounts for many factors including economic viability to a given entity, level of technological capability, legal disclosure obligations, benefits and potential for investment a company might get from publishing uncertainty findings. The current Society of Petroleum Engineers (SPE) Petroleum Resource Management System (PRMS), historically provided decision points based on "commercial/business/financial/Securities and Exchange Commission (SEC)" goals.

The culmination is a matrix of "certainty" of being able to commercially extract a given resource.

- ***In space, this measure of certainty plays directly into the choice of lading site selection, constructing sustainable human infrastructure and resource mining and processing. - A chicken vs egg problem.***

- ***Certainty in space must be much greater than on the Earth. Prospecting in space therefore must be more rigorous and well defined. You will not have the luxury of drilling a "dry hole" in space.***

Reference History: McKelvey, 1972; Brobst & Pratt, 1973, Pratt & Brobst, 1974; Voelker, 1979; Geological Survey Circular 831, 1980, Taylor and Steven, 1983; Goudarzi, 1984; SPE PRMS 2007, 2011; Schulz et al., 2017

Developing/Defining a **Planetary Resource Management System (PRMS)**

- **Reserves:** Those quantities of resources anticipated to be commercially recovered from known accumulations from a given date forward under defined conditions. To be classified as “reserves” you first need to establish commercial certainty of extraction using existing technology. Quantities should not be classified as reserves unless there is an expectation that the accumulation will be developed and placed in production within a reasonable timeframe.

  - Uncertainty Categories: **Proved** reserves are limited to those quantities that are commercial under current economic/technical conditions, while **Probable** and **Possible** reserves may be based on future economic/technical conditions.
  - ***For space, anything below “possible”, i.e. less than a 50% certainty of being able to commercially extract the resource with currently available technology falls into the ‘prospective-resources’ or ‘contingent-resources’ categories***.

- **Contingent Resources:** Those quantities of resources estimated on a given date as potentially recoverable from known accumulations, but which are not currently considered to be “commercially” recoverable because of commercial/technical abilities are not considered mature enough to proceed. The probability for the contingent resources to become economically recoverable is significantly lower than for proven, probable or possible reserves (volumes are highly speculative).
- **Prospective Resources:** Those quantities of resources which are estimated, on a given date, to be potentially recoverable from undiscovered accumulations (an estimated potentially recoverable portion of Undiscovered Resources-Initially-in-Place.

http://www.spe.org/industry/reserves.php

Developing/Defining a <u>**Planetary Resource Management System (PRMS)**</u>

- **Range of Uncertainty:** Any estimation of resource quantities (Proved, Probable, Possible, Low, Best and High) for a given accumulation is subject to technical, government and commercial uncertainties, and should be quoted as a range that closely approximates the **quantities that will actually be recovered** from the accumulation.
  - ***For space resources, uncertainty categories need to be very precisely defined (maybe before "prospecting" even starts).***

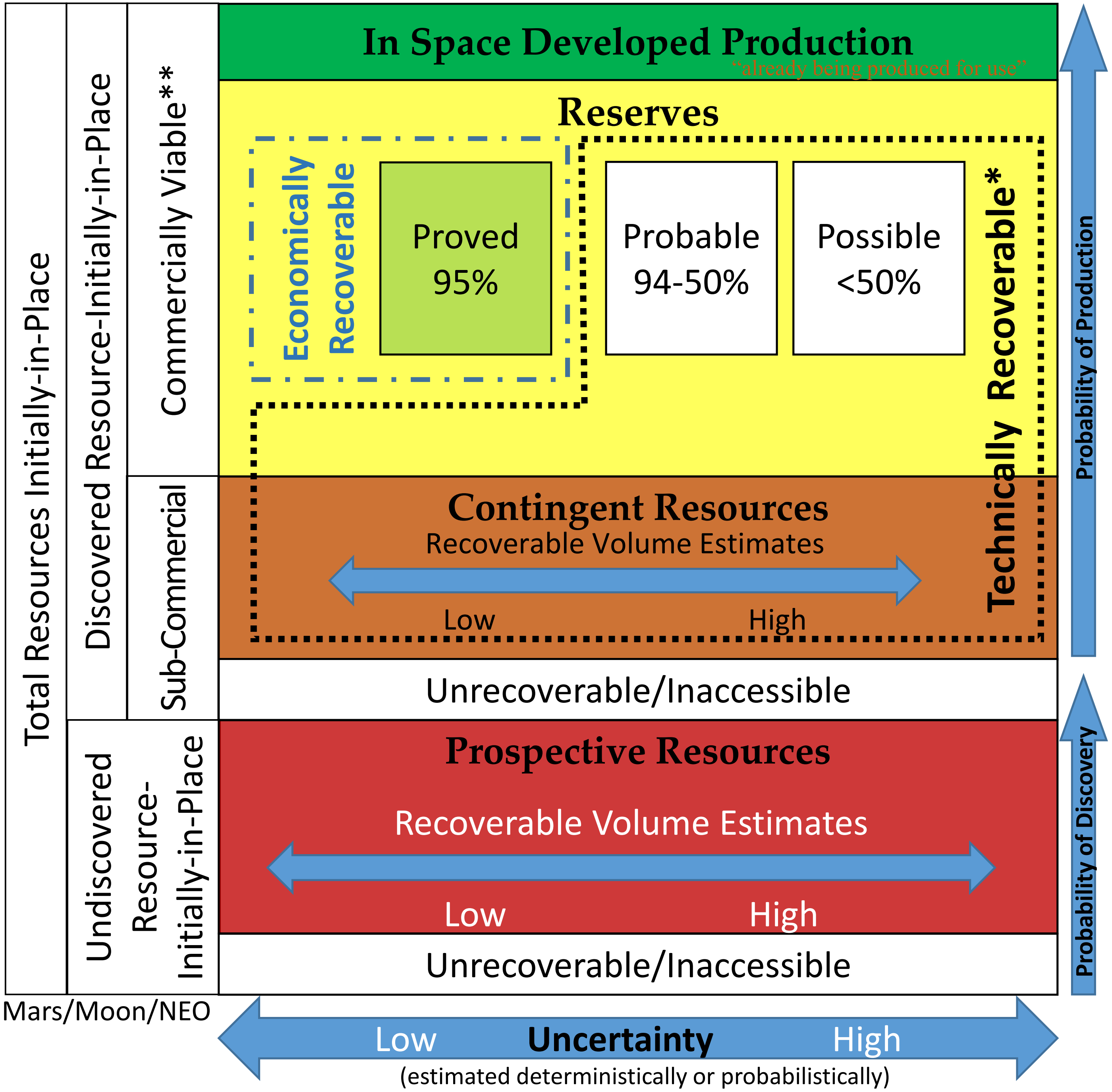
  In all cases the actual **uncertainty will depend on the amount and quality of data** (both technical and commercial) that is available for that accumulation. As more data become available for a specific accumulation, probabilistic methods should be used, and the range of uncertainty for that accumulation should be reduced/redefined.

Other Definitions:

- **Total Resources Initially-in-Place:** that quantity of resources that is estimated to exist originally in naturally occurring accumulations. It includes that quantity of resources that is estimated, as of a given date, to be contained in known accumulations prior to production plus those estimated quantities in accumulations yet to be discovered (equivalent to "total resources").
- **Discovered Resources Initially-in-Place:** that quantity of resources that is estimated, as of a given date, to be contained in known accumulations prior to production.
- **Undiscovered Resources Initially-in-Place:** that quantity of resources estimated, as of a given date, to be contained within accumulations yet to be discovered.

http://www.spe.org/industry/petroleum-resources-classification-system-definitions.php

Planetary Resources Management System



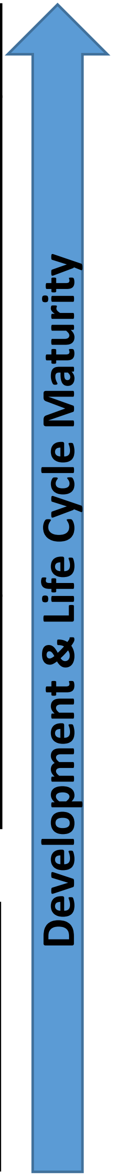
Site Selection & ISRU

A reasonable assessment of future economic support, resource needs determined, available space and surface transportation and infrastructure, adequate surface mining technologies, sustainable & operational safety.

Reserves located on or near the surface (GPR/GRS) using multiple verities of remote data , including ground truth, that provides *quantitative evidence of amounts and accessibility (t-6 to 18 years)*

Potentially recoverable volumes identified using current assets on site.
Initial estimates of recoverable volumes using (Vis-IR, Photo, Neutron, Multispec, etc.)

Prospecting mission operation, time to find and data reduction from current assets (t-5 to 8 years)	Developing new tools to locate/Identify potentially recoverable volumes (Vis-IR, Photo, Multispec, Neutron, etc.)



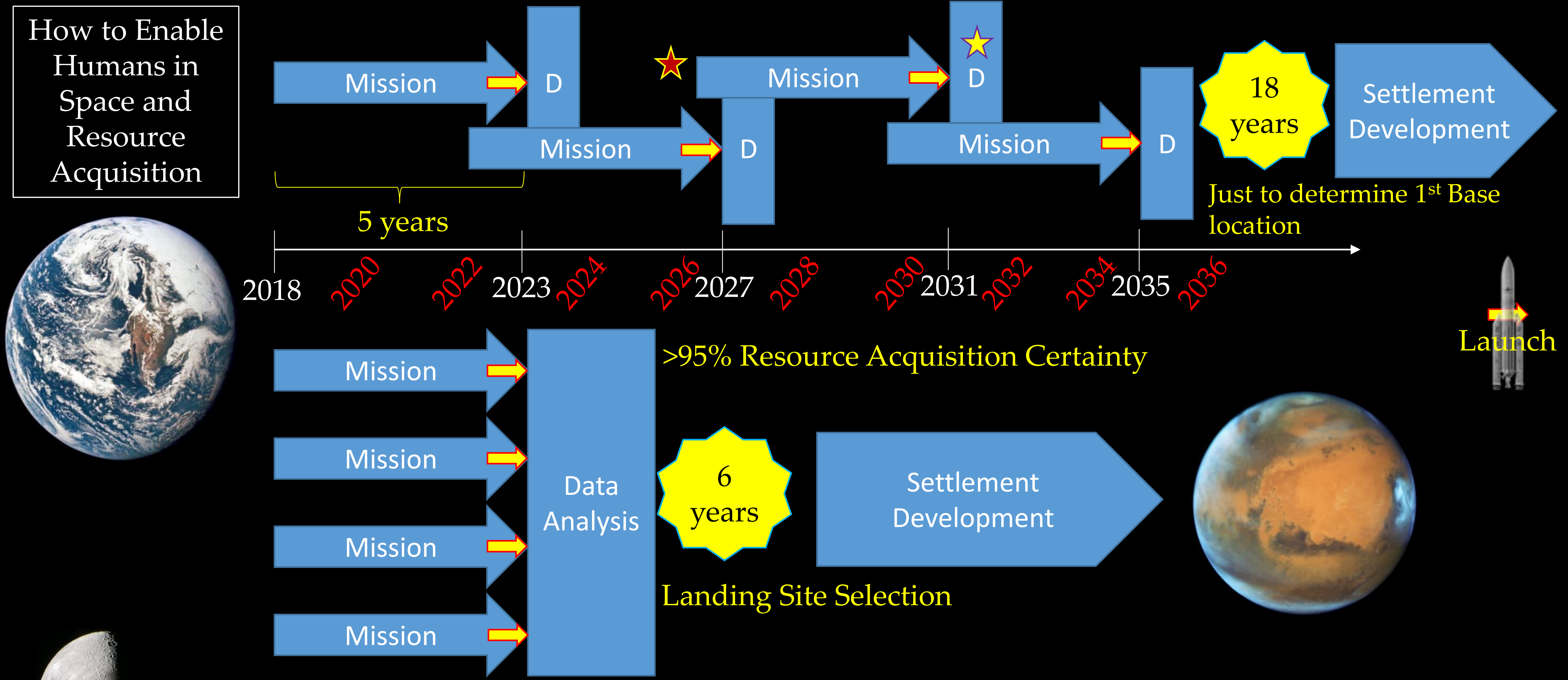
* total technologically extractable amount is the producible fraction.

** The term "Commercial" is a proxy for to be Developed Resources that are efficiently acquired, usable for in-space sustenance and sustainability, and not necessarily bought/sold.

Moon Water Prospecting

Reference	Technique/Tools	Location	Resource Categorization	Recoverable Volume Estimation (?)
Goddard, 1920	modeling, physics	Lunar Poles	Undiscovered Prospective Resource	Low
Urey, 1952	modeling, physics	Sheltered surfaces	Undiscovered Prospective Resource	Low
Nozette et al., 1996	Bistatic Radar Experiment	South Pole	Undiscovered Prospective Resource	Low
Feldman et al., 1998	Orbital Neutron Spectroscopy	Lunar Poles	Undiscovered Prospective Resource	Low
Teodoro et al., 2010	Neutron Pixon Image Algorithm	Permanently Shadowed Regions (PSRs)	Undiscovered Prospective Resource	Low; H concentration of ~1 wt% water
Pieters et al., 2009	Near Infrared (NIR) on M^3	Dayside Surface	Undiscovered Prospective Resource	Low; ~0.3 wt% water in upper 1-2 mm regolith
Sunshine et al., 2009	High-Resolution Inst.- Infrared Spect. (HRI-IR)	Dayside Surface	Undiscovered Prospective Resource	Low; ~0.3 wt% water in upper 1-2 mm regolith
Clark et al., 2009	Visible And Infrared Mapping Spect. (VMIS)	Dayside Surface	Undiscovered Prospective Resource	Low; ~0.3 wt% water in upper 1-2 mm regolith
Colaprete et al., 2010	LRO & LCROSS – NIR and	Cabeus (PSR impact plume)	Discovered Contingent (Low) Resource	Low; 5.6 ± 2.6 wt% water in upper micron regolith
Gladstone et al., 2012	Lyman Alpha Mapping Project (LAMP)	Polar PSR craters	Discovered Contingent (Low) Resource	Low; 1-2 wt% water frost layer in upper micron regolith
Sanin et al., 2017	Lunar Exp. Neutron Det. (LEND)	Polar PSR craters	Discovered Contingent (Low) Resource	Low; 0.34-0.54 wt% top 1 m

NEW PARADIGM NEEDED: Sequential vs Parallel, Robotic Only Prospecting Mission Architectures



This paradigm is less pronounced for the Moon (due to proximity), but equally important for establishing operational conditions in a reasonable amount of time.

★ What happens when administration changes ?

★ What happens when this path proves incorrect…open ?

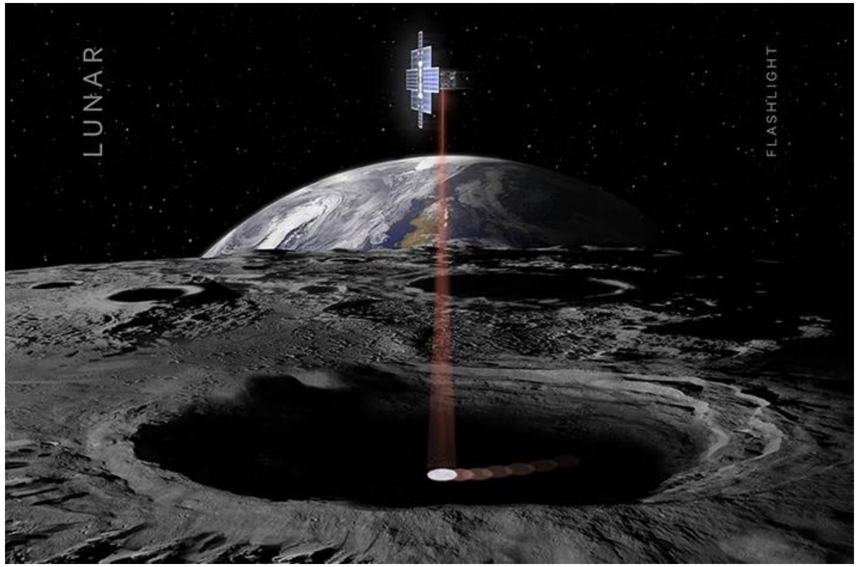
Cube Sat Revolution… is it viable for planetary prospecting?

Could prospecting be done with a fleet of cube/small satellites (e.g., http://deepspaceindustries.com/xplorer/).

The answer is MOST LIKELY NO, but there are could be some useful aspects:

1) Remote Sensing – continued knowledge production (the only prospecting component)
    a. For the Moon, NASA is developing several CubeSat orbital missions (Lunar Flashlight, LunaH-MAP, and Lunar IceCube), specifically aimed at trying to better locate where water ice might be found and how much water ice might be available. https://www.nasa.gov/isru

2) Monitor Surface System Performance/Progress,
3) Relay Communications,
4) Longevity (?).

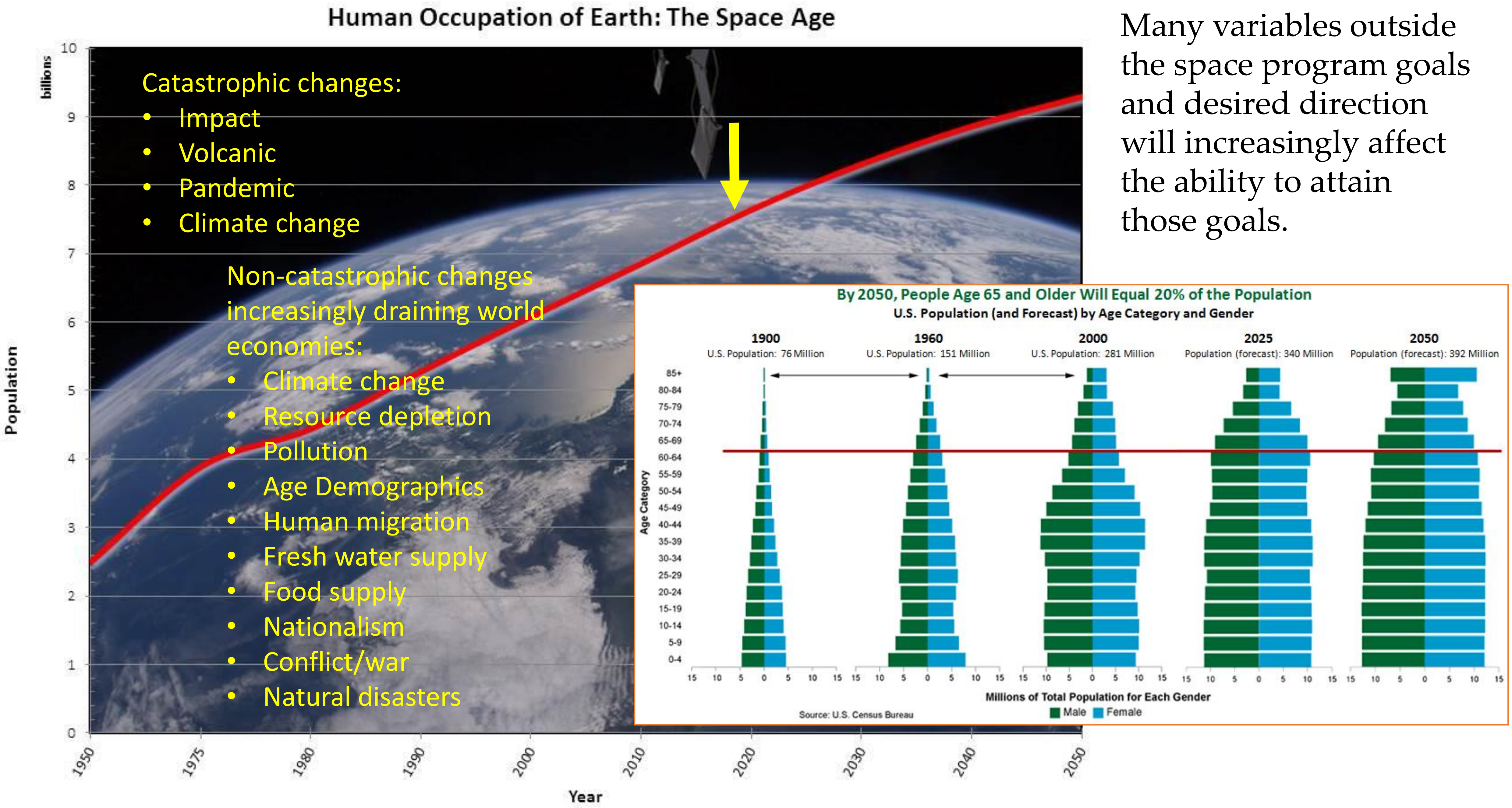


https://www.jpl.nasa.gov/cubesat/missions/lunar_flashlight.php

Ultimately, to achieve a reliable and valid estimation of accumulation volumes/quantities, assets need to be placed on the surface (whether human or robotic), and which can,

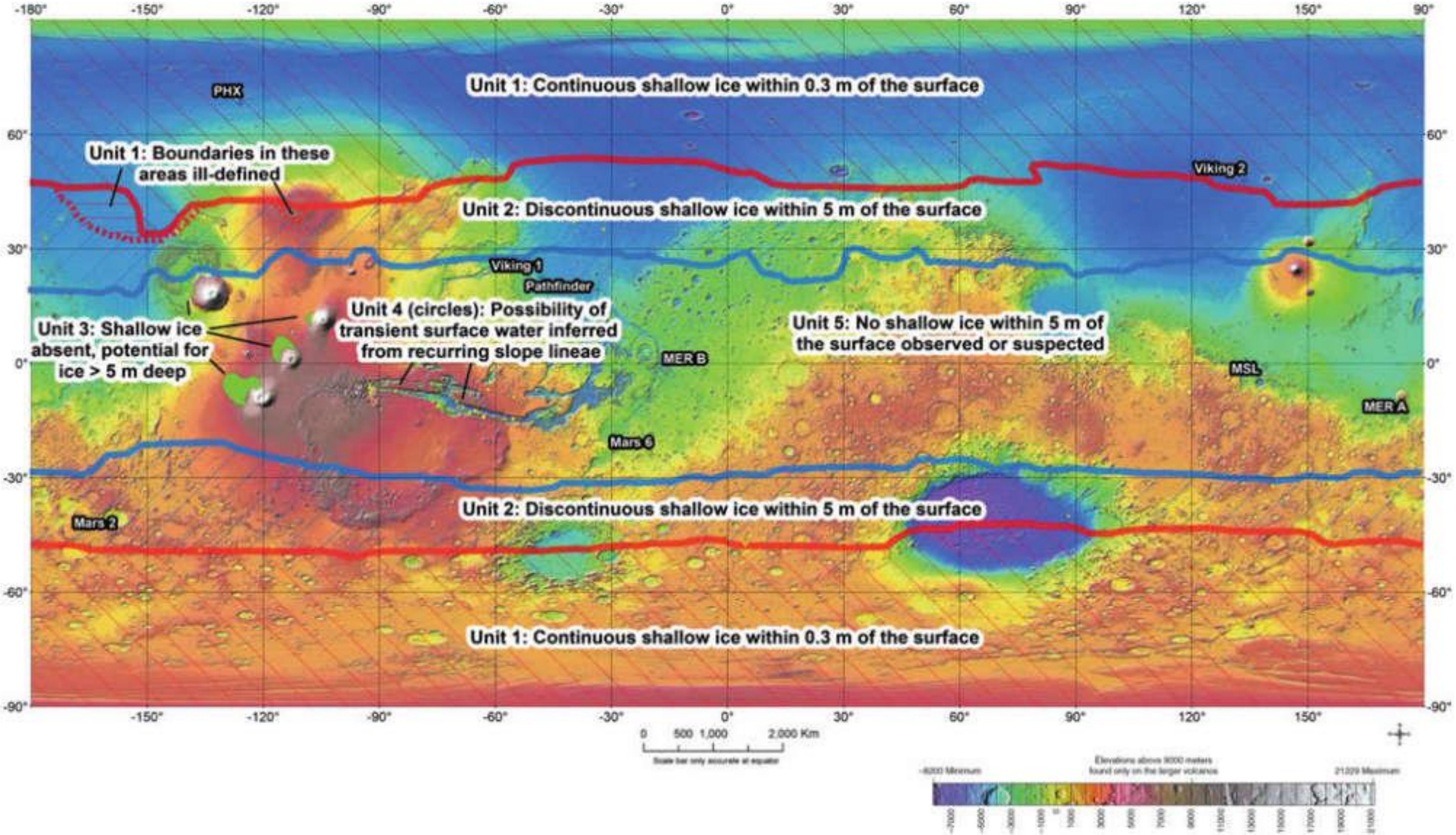
1) Dig, drill, taste and smell everything,
2) Quantitatively measure needed variables that will allow a highly accurate determination of resource volumes to reduce estimate errors,
3) Assess surface technical, operational and mining constraints and needs.

External Constrictions to Settlement and Resource Acquisition (Earth) - Example



Many variables outside the space program goals and desired direction will increasingly affect the ability to attain those goals.

External Constrictions to Settlement and Resource Acquisition (Mars Case - Planetary Protection) - Example



Take Away SRR/PTMSS Workshop 2018

1. A definitive, commercially viable **need** is required to engage mining in space, including knowing the users for those materials. It remains questionable whether anything mined in space would ever be brought back to Earth, especially the near term (50+ years)?

2. Refine PRMS to show correct numerical uncertainties in the knowledge of all desired space resources.

3. Enhance TRL levels of all associated space prospecting, transportation, habitation and mining technologies.

4. Shift focus and verbiage to "Settlement" with an emphasis on sustainability, permanence and definable long term goals. They will be the miners and users in space.

5. Should stop using the term "Exploration" as it implies short term, fragmented thought, action and behavioral processes and responses.

6. Should stop selling "Science" as the end all reason for advancing into space.

7. Use a parallel (nearly parallel) prospecting mission design to focus analysis and site selection to occur within a reasonable and accomplishable timetable (no matter what outside inhibiting drivers emerge).

8. Begin concentrated and well defined "prospecting" efforts at Moon or Mars – whichever is the current favored destination of the day.